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Working Group 1 Summary for the 2006 FFAG Workshop at KURRI

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Abstract. This paper summarizes the workshop presentations at the 2006 FFAG Workshop at KURRI related to FFAG use for muons. The particular topics covered were harmonic number jump acceleration, ionization cooling, PRISM and muon phase rotation, tracking and error analysis, and our understanding of scaling and non-scaling FFAGs.

Keywords: Fixed Field Alternating Gradient Accelerator; Harmonic Number Jump; Ionization; Tracking; Errors
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INTRODUCTION

One of the most important uses envisioned for FFAGs is for handling muon beams. The large beam sizes and energy spreads in muon beams make them ideal candidates for being manipulated by FFAGs.

The 2006 FFAG Workshop at KURRI discussed several aspects of FFAGs related to their use with muons:

- Harmonic number jump acceleration
- Ionization cooling
- PRISM and muon phase rotation
- Tracking and error analysis
- Improving our understanding of scaling and non-scaling FFAGs

This paper summarizes the workshop presentations in these areas, even in some cases when they weren't specific to muons. Individual papers in these proceedings should be consulted for more detailed information and references.

HARMONIC NUMBER JUMP ACCELERATION

High frequency RF cavities (generally in the 200 to 400 MHz range) are good for accelerating muons due to the relatively high gradients that can be achieved in them. At higher energies, one uses non-scaling FFAGs since they can be made isochronous within their energy range. At lower energies, the time of flight dependence on transverse amplitude makes the use of non-scaling FFAGs problematic, although some methods of addressing this problem were presented. Instead, one might consider using a scaling FFAG with room-temperature magnets. Harmonic number jump acceleration, where the harmonic number changes with every turn, allows one to use a scaling FFAG with high frequency RF despite the fact that it is non-isochronous throughout its energy range. Some sample parameters for such machines are

Type	Spiral	Triplet	Spiral
Radius (m)	25	200	40
Field Index	20	150	38
Harmonic Number	200	1200	320

The primary difficulty related to using harmonic number jump acceleration for muon acceleration is that the ring needs to be filled with cavities to maintain an adequate gradient. While the harmonic number cannot be maintained at an integer for all turns for all cavities, in appears that one can come sufficiently close to doing so, as shown in Fig. 1. The method used there is only approximate, and needs significant further refinement.

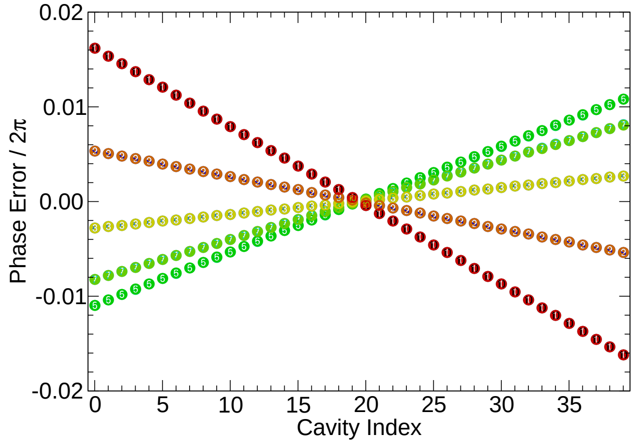

FIGURE 1. Phase error as a function of cavity index (position in the ring) and pass number (number in the circle, starting from 1) when using harmonic number jump acceleration. Note that 10 cavity passes are shown here; the last 5 and the first 5 have identical phases.

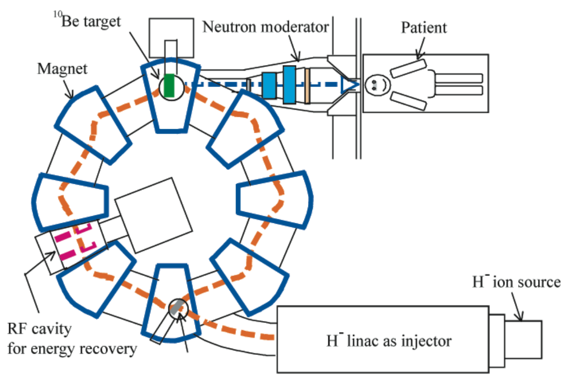

FIGURE 2. The ERIT ring.

IONIZATION "COOLING" IN FFAGS

Several applications of FFAGs passed the beam through a material to manipulate the beam emittances:

- In ERIT (see Fig. 2), protons impinge on a wedge-shaped Be target. The wedge shape of the target increases the amount of time that the beam can remain in the ring by reducing the rate at which the energy spread increases. This machine has been designed and funded.
- Similarly, one could use an ion beam interacting with a gas target to produce radioactive ions for a beta beam (see Fig. 3). The gas target is shaped to maintain cooling in all phase space planes, thus allowing the ion beam to remain in the ring for an extended time, improving the efficiency.
- An FFAG ring could be used for ionization cooling of muons (see Fig. 4).

FFAGs are useful for these applications due to the large energy acceptances required to handle the beams.

PRISM AND PHASE ROTATION

PRISM (see Fig. 5), a machine for phase rotating muons from large to small energy spread, is under construction. Unfortunately, there is not enough money to complete all of the cavities. There are, however, ideas in how to improve

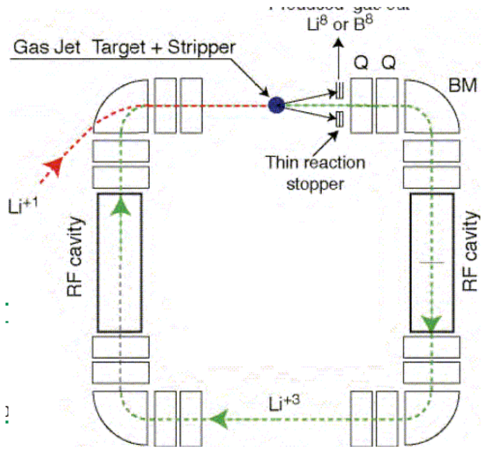

FIGURE 3. A ring for the production of radioactive ions. The design shown here is not an FFAG, but it could be in principle.

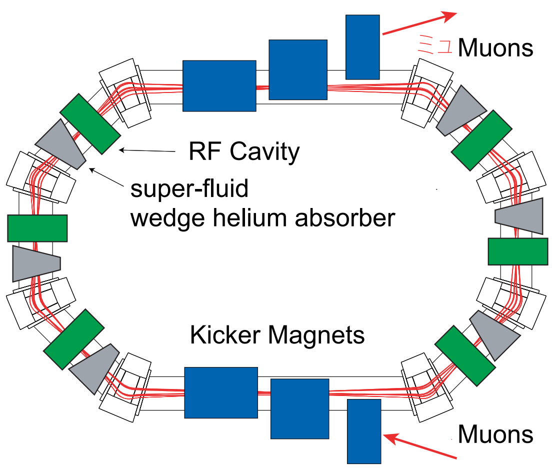

FIGURE 4. An ionization cooling ring, using FFAGs for arcs.

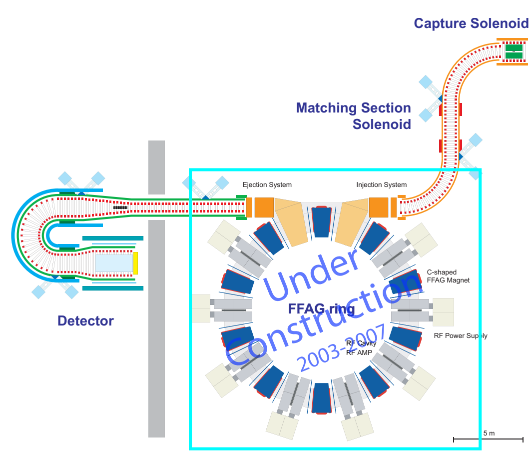

FIGURE 5. PRISM.

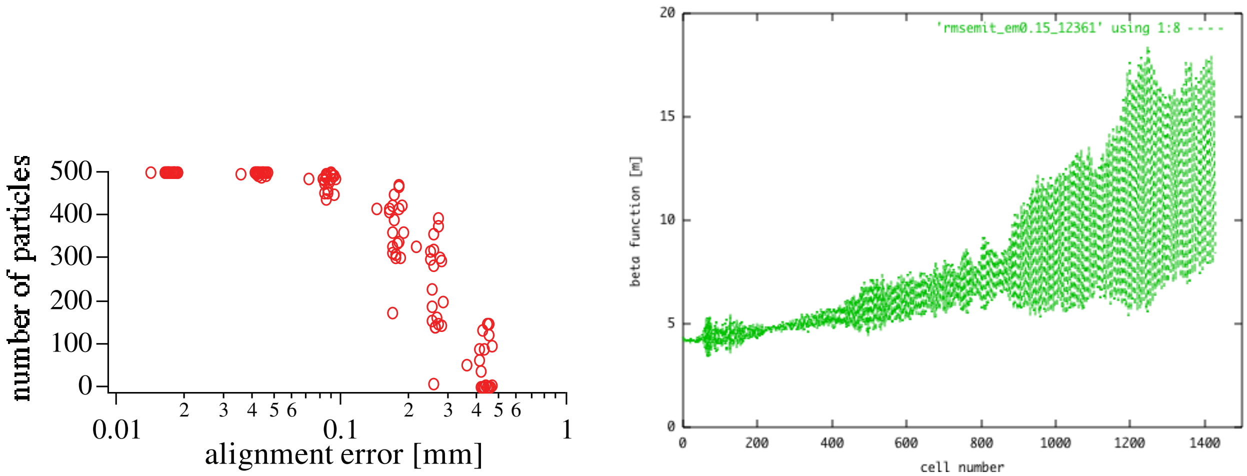

FIGURE 6. Particle loss as a function of r.m.s. alignment error (left), and the beam beta function as a function of turn number (right, the figure is showing rapid oscillations) in an example muon FFAG.

cavity performance: one could improve the magnetic alloy core impedance, or one could use ceramic cavities.

There was also some discussion of using a PRISM-like lattice to perform muon phase rotation in a neutrino factory or muon collider.

TRACKING AND ERROR ANALYSIS

The breaking of the lattice symmetry due to errors can be an important source of emittance growth in FFAGs. Work is being performed on error analysis (see Fig. 6) for non-scaling muon accelerators as well as EMMA (an electron model for a linear non-scaling FFAG). We are beginning to understand the source of the emittance growth in these machines: there appears to be an envelope mismatch which leads to the beam ellipses having large amplitudes, which are then distorted by nonlinearities. Some growth seems to occur due to the $\nu_x - 2\nu_y = 0$ resonance.

UNDERSTANDING OF SCALING AND NON-SCALING FFAGS

Non-scaling FFAGs tend to have relatively small apertures when compared with scaling FFAGs. However, this comes at a cost: large chromaticity. A non-scaling FFAG with very small chromaticity was constructed; the machine ended up looking very similar to a scaling FFAG, including the larger aperture.

CONCLUSIONS

FFAGs are finding expanded uses, in particular for ionization cooling and similar manipulations, as well as for the phase rotation of muons. We are increasing our understanding of FFAGs and coming up with more ideas for how to apply them: non-scaling FFAGs are being designed with low chromaticity, the effect of errors in FFAGs is being understood better, and we are studying harmonic number jump acceleration with rings containing many cavities. PRISM is proceeding with construction, and cavity R&D is continuing.

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